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THE WARM-AIR HEATING RESEARCH RESIDENCE IN ZERO WEATHER

BY

VINCENT S. DAY

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ENGINEERING EXPERIMENT STATION

CIRCULAR NO. 15 MAY, 1927

THE WARM-AIR HEATING RESEARCH RESIDENCE IN ZERO WEATHER

RESULTS OBTAINED AS A PART OF THE
WARM-AIR FURNACE INVESTIGATION

CONDUCTED BY
THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH
THE NATIONAL WARM-AIR HEATING AND
VENTILATING ASSOCIATION

BY
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ENGINEERING EXPERIMENT STATION
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THE WARM-AIR HEATING RESEARCH RESIDENCE IN ZERO WEATHER

I. Introduction

1. *Introductory Remarks.*—The coöperative agreement between the National Warm-Air Heating and Ventilating Association and the University of Illinois, which has been in effect since October, 1918, provides for the investigation of warm-air furnaces and furnace heating systems. Under the terms of this agreement a very extensive study* of furnace heating problems has been made, using first an experimental plant with auxiliary equipment in the laboratory, and later a typical modern residence erected by the Association for the express purpose of correlating and extending the work in the laboratory to the conditions of actual installation.

The work in the research residence has been in progress for the past three heating seasons and a great quantity of valuable data relating to the performance of a warm-air furnace heating system has been obtained. These data are of first importance to the designers, installers, and owners of such heating systems, covering as they do all the weather conditions encountered during the heating season. Naturally, the greatest interest in the performance of any heating plant attaches to the records secured under the worst weather or load conditions. The blizzard and cold wave of January 13th, 14th, and 15th, 1927, provided an exceptionally good opportunity of studying typical warm-air heating plant performance under maximum load conditions, and this circular summarizes the more important results obtained over a 48-hr. period during which the outside temperature averaged — 3.1 deg. F. A future bulletin of the Engineering Experiment Station will present complete results and comparisons of different systems for a period of several heating seasons.

A photograph of the research residence taken during the snowstorm and cold weather with which this circular deals is shown in Fig. 1.

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*"Report of Progress in Warm-Air Furnace Research," Univ. of Ill., Eng. Exp. Sta., Bul. 112, 1919.

"Emissivity of Heat from Various Surfaces," Univ. of Ill., Eng. Exp. Sta., Bul. 117, 1920.

"Investigation of Warm-Air Furnaces and Heating Systems," Part I, Univ. of Ill., Eng. Exp. Sta., Bul. 120, 1921.

"Investigation of Warm-Air Furnaces and Heating Systems," Part II, Univ. of Ill., Eng. Exp. Sta., Bul. 141, 1924.

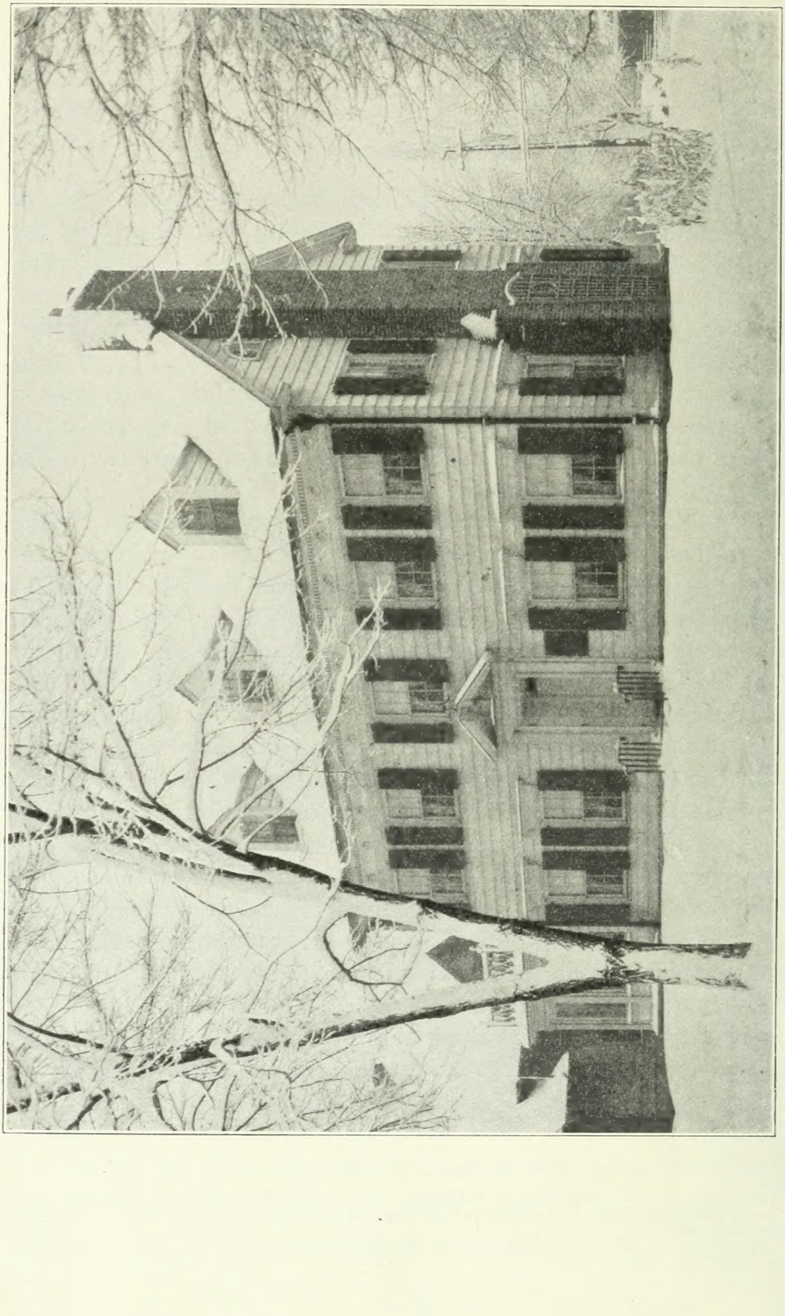

Fig. 1. Warm-air Heating Research Residence During Heavy Snowfall

FIG. 2. INTERIOR OF RESEARCH RESIDENCE

2. *Acknowledgments.*—The tests with which this circular deals have been a part of the work of the Engineering Experiment Station of the University of Illinois, of which Dean M. S. Ketchum is the director.

The prosecution of this work and the preparation of the results for publication have been in charge of A. C. Willard, Professor of Heating and Ventilation, and Head of the Department of Mechanical Engineering, who originated the investigation, assisted by A. P. Kratz, Research Professor, and by the author of this circular, who devotes his entire time to the investigation. Since September 1, 1926, Mr. J. F. Quereau, Research Graduate Assistant, has been attached to the staff of the investigation.*

II. THE RESEARCH RESIDENCE

3. *Description of Residence.*—In all respects, the research residence is of standard frame dwelling construction, with the single ex-

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*At the time of building the research residence, Prof. L. H. Provine, head of the Department of Architecture, acted as architect, and he was assisted by C. A. Kissinger, a member of the staff of the same department.

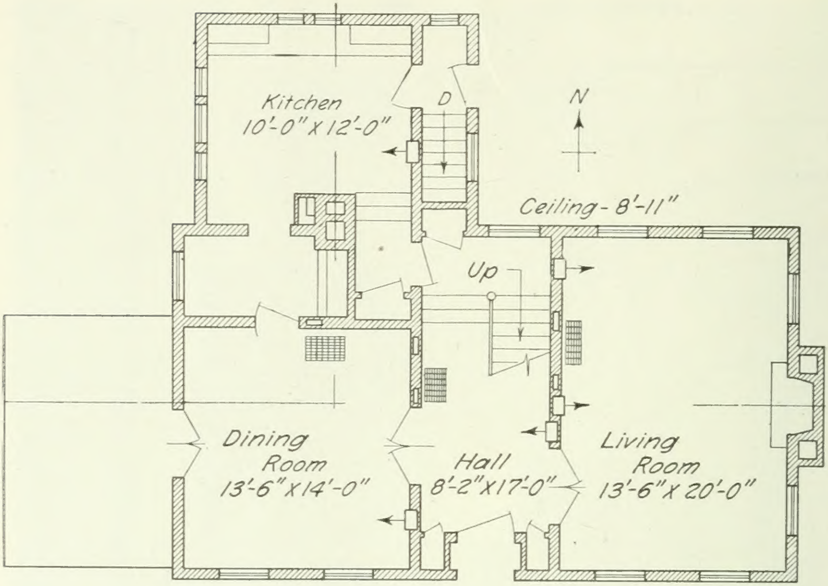

Fig. 3 First Floor Plan with Location of Warm-air Registers and Cold-air Return Grilles

ception of the studding, which is 2 in. by 6 in. instead of the usual 2 in. by 4 in. This, according to the commonly accepted theory of heat transmission of walls, operates to increase the wall heat loss, but permits the use of larger wall stacks than could be used in 2 in. by 4 in. construction. The wall section is as follows: weather boarding, building paper, ship-lap siding on 2 in. by 6 in. studding, lath, and plaster with rough sand finish. The coefficient of heat transmission for this wall section is 0.20 B.t.u. per sq. ft. per hr. per 1 deg. F., at a wind velocity of 15 mi. per hr. The walls were not insulated, nor was weather stripping used at the windows and doors. Interlocking copper shingles were used on the roof.

The research residence has not been occupied by a family. Instead, a caretaker has lived in the residence, and the daily occupants have been the members of the research staff. Furniture, rugs, and window shades and curtains were provided, and Fig. 2 suggests the completeness of furnishing. No cooking or other domestic processes requiring the application of heat were carried on. Thus the kitchen, as well as all other rooms, received heat solely from the heating system.

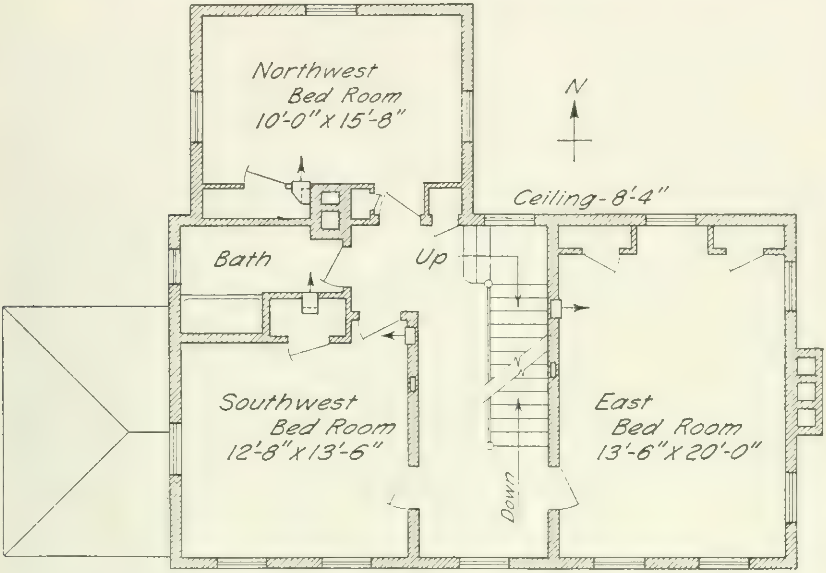

FIG. 4. SECOND FLOOR PLAN WITH LOCATION OF WARM-AIR REGISTERS

All the room doors were open during the tests covered by this circular, with the exception of those of the sun-room, which was not connected to the heating plant at this time.

The room arrangement and exposures are shown in Figs. 3, 4, and 5. It is important to note that only one room, the bath room, has a single exposure to the weather, and that throughout the residence the proportion of glass area to wall area is high. Hence the heating problem is not an easy one. The heat losses calculated by the usual methods are approximately 119 000 B.t.u. per hr. at 0 deg. F. and 15 mi. per hr. wind velocity.

4. *Heating Plant.*—The locations of the warm-air registers and cold-air return grilles are shown in Figs. 3, 4 and 5. Details of piping and furnace are shown in Fig. 6, and given in Tables 1 and 2.

The particular heating layout shown is by no means the only plan possible, nor is it a model one. The plant is simply one of a series in which a comparison of cold-air return locations is being made, and was undergoing test during the period of cold weather covered by this discussion.

Three return ducts, compactly arranged with the grilles located near the inner walls of the rooms, were used. In the design of the

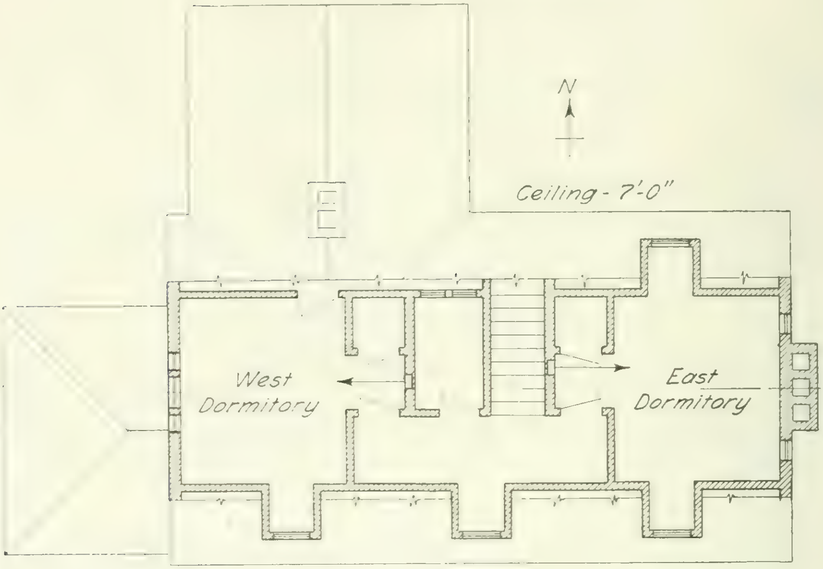

FIG. 5. THIRD FLOOR PLAN WITH LOCATION OF WARM-AIR REGISTERS

cold-air return ducts, abrupt changes of section and direction were avoided; and ample area, in excess of the total warm-air-pipe area, was maintained at all points. These are fundamental precautions to be observed in good design.

The heater was of a common cast-iron type, and had a grate area of 2.88 sq. ft. The smoke pipe, 10 in. in diameter and 10 ft. in length, was connected to a 12-in. by 12-in. firetile-lined flue, which was 35 ft. high. This chimney passed up through the house, and hence the heat transmitted through its 8-in. brick walls was given up to the house and was useful in heating. A cross damper in the smoke pipe, 3 ft. from the furnace, was used to restrict the draft. The check draft was sealed.

The heat pipes and fittings, eleven in number, were of standard commercial sizes and types, no effort being made to obtain streamline flow by the use of special fittings. All pipes were of bare bright tin, except for narrow sealing strips of asbestos paper at the joints, previous tests having demonstrated that the asbestos paper covering on bright tin plates is wasteful of heat.* The diameters of the pipes were based on heat loss calculations for the various rooms, the "Standard Code

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* "Emissivity of Heat from Various Surfaces," Univ. of Ill. Eng. Exp. Sta., Bul. 117.

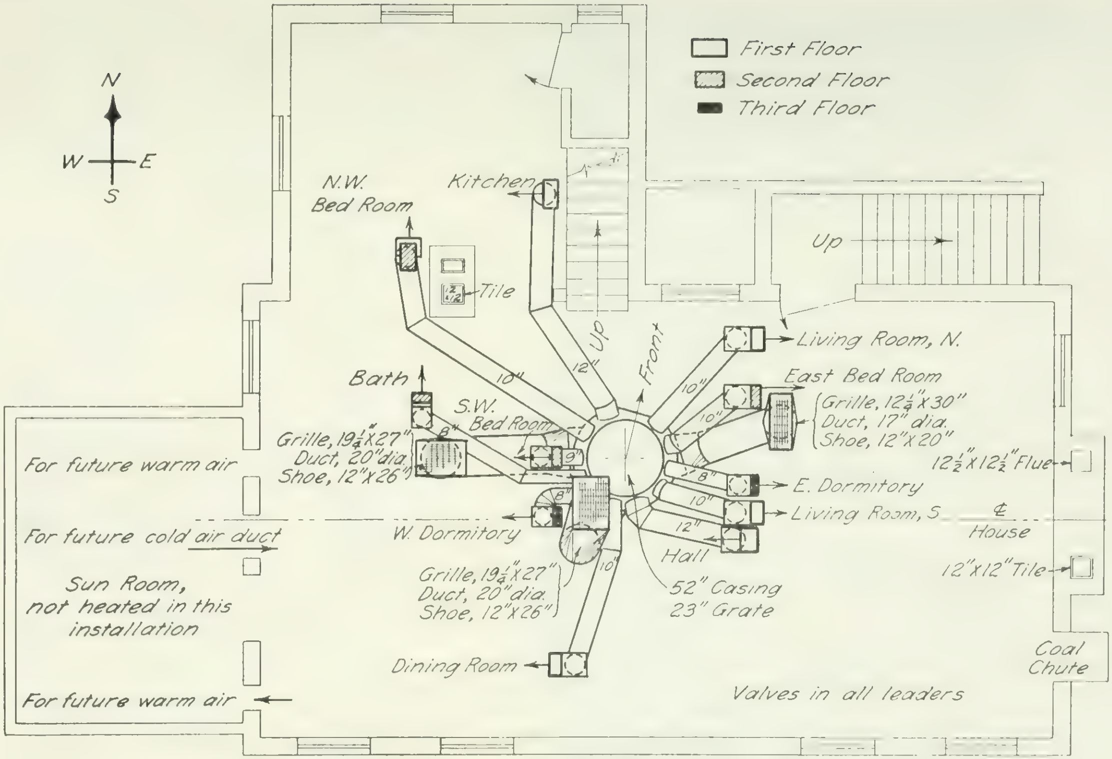

Fig. 6. Plan of Heating Plant Known as Third Installation

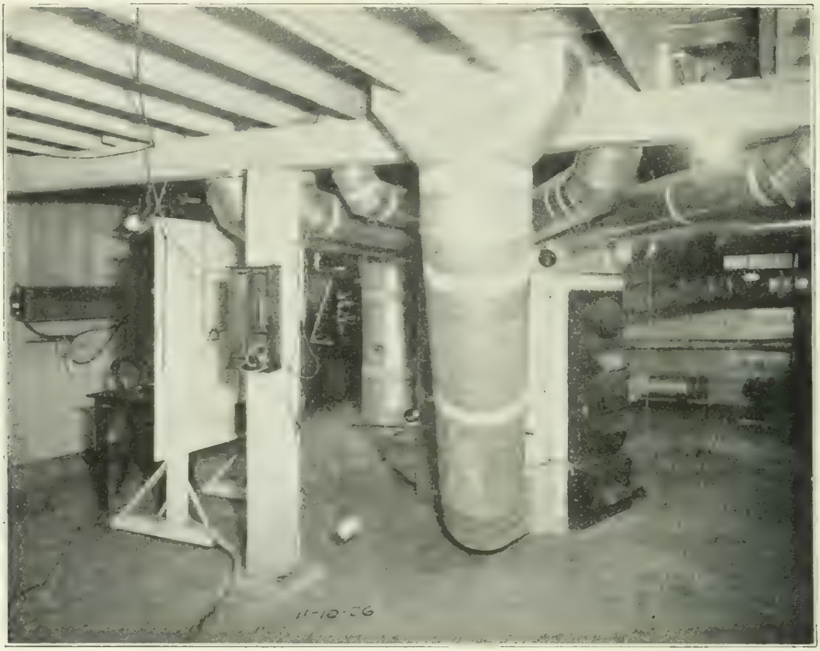

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Fig. 7. View of Heating Plant

Regulating the Installation of Warm-Air Heating Systems,"* being used for this purpose. The wall stacks, the concealed vertical portion of the heat pipes, were of mixed construction, some being of double tin with intervening air space, and others of single tin construction. The cross-sectional area of the stacks was over 70 per cent of the area of the basement heat pipes to which they were connected. Registers were of commercial types and sizes and, in this particular installation, were all of the wall type.

It has been the object in this description of the research residence and the heating plant to show that both were standard, rather than special, and that, therefore, the data for sub-zero weather, which follow, are such as might be obtained in any well designed warm-air heating plant.

---

*That part of the Standard Code dealing with pipe sizes is based on results secured in the investigation now in progress at the University of Illinois.

TABLE 1

PIPE, STACK, AND REGISTER SIZES

Floor	Room	Leaders		Stacks (or throats)			Registers		
		Dia. in.	Area sq. in.	Size in.	Type	Area sq. in.	Size in.	Free Area sq. in.	Free Area % of Total
First	Living Room, N.	10	78.5	5½ x 13	Double	71.5	10 x 12	83.5	70
	Living Room, S.	10	78.5	5½ x 13	Double	71.5	10 x 12	83.5	70
	Hall	12	113.0	7$\frac{9}{16}$ x 14	Single	106.0	12 x 14	120.5	72
	Dining Room	10	78.5	5½ x 13	Double	71.5	10 x 12	83.5	70
	Kitchen	12	113.0	7 x 14	Single	98.0	12 x 14	120.5	72
Second	E. Bed Room	10	78.5	5 x 12	Single	60.0	10 x 12	83.5	70
	S. W. Bed Room	9	64.0	3½ x 12	Single	42.0	9 x 12	74.0	69
	Bath Room	8	50.0	3 x 10	Double	30.0	8 x 10	53.0	67
	N. W. Bed Room	10	78.5	5½ x 13	Double	71.5	10 x 12	83.5	70
Third	E. Dormitory	8	50.0	3 x 10	Single	30.0	8 x 10	53.0	67
	W. Dormitory	8	50.0	3 x 10	Double	30.0	8 x 10	53.0	67
TOTALS									
First			461.5			417.5			
Second			271.0			203.5			
Third			100.0			60.0			
Total			832.5			681.0			

TABLE 2
COLD-AIR RETURN DUCT SIZES
All cold-air return grilles on first floor.

Location	Free Area of Grilles* sq. in.	Area of Ducts sq. in.	Area of Shoes sq. in.
East	219	226	240
West	312	314	312
South	312	314	312
Total	843	854	864

*The free area of the grilles is 60 per cent of the total area.

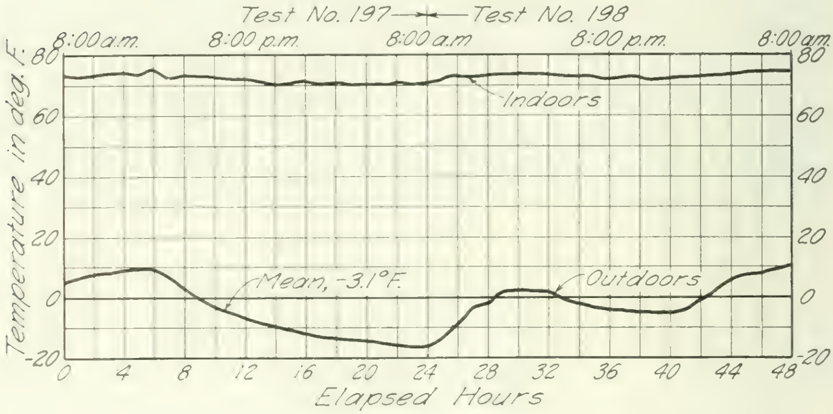

FIG. 8. GRAPHICAL RECORD OF OUTDOOR AND INDOOR TEMPERATURES FOR THE PERIOD OF THE TESTS

III. SUB-ZERO WEATHER TESTS

5. *Weather Conditions.*—For two days following a heavy snowfall the temperature averaged below zero, the minimum being − 16 deg. F. and the maximum 10 deg. F. The mean temperature for the period was − 3.1 deg. F. A graphical record of the temperatures is shown in Fig. 8.

At the cessation of the snowfall the barometer rose to 30.10 in., and clear skies prevailed during the two days. On the first day the wind velocity rose to 14 mi. per hr. but subsided to 5 mi. per hr. on the second day. The wind direction was northwest, shifting to west on the second day.

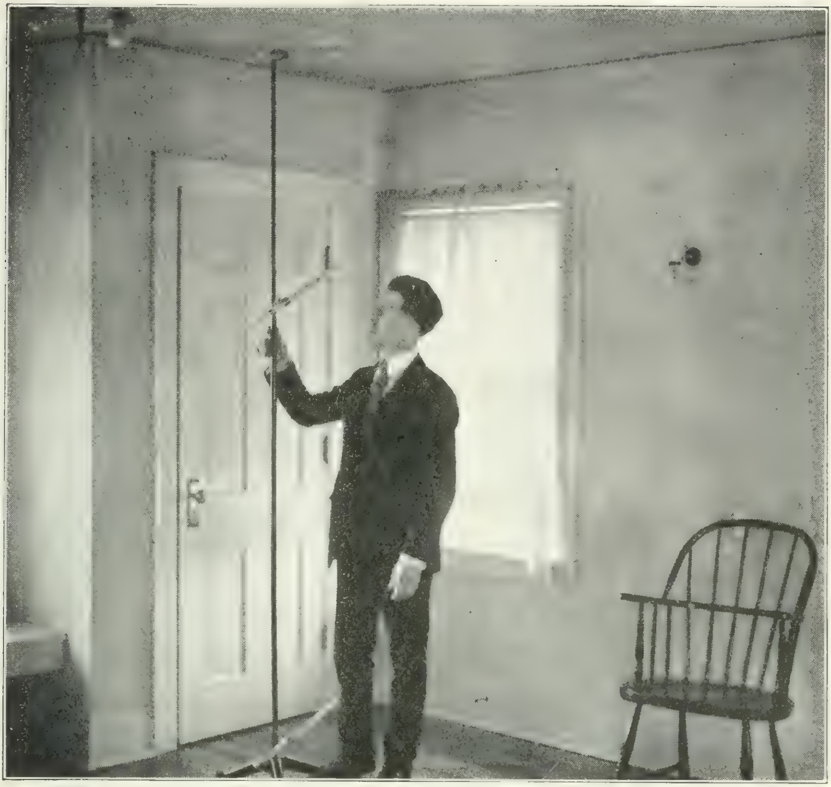

FIG. 9. THERMOMETER STANDARDS FOR FLOOR, BREATHING-LEVEL, AND CEILING TEMPERATURES IN EACH ROOM

6. *Temperatures in Residence.*—The following are the average temperatures at the breathing level in the center of the various rooms of the residence, each temperature being the average of ten readings, five being made each day.

First floor	Deg. F.	Second floor	Deg. F.	Third floor	Deg. F.
Living Room	73.1	E. Bed Room	79.5	E. Dormitory	69.7
Dining Room	71.4	S. W. Bed Room	74.7	W. Dormitory	71.3
Kitchen	70.3	N. W. Bed Room	72.1		
Hall	73.5	Bath Room	75.2		

Average 73.1 deg. F.
Variation from average, plus 6.4 and minus 3.4 deg. F.
Outdoor —3.1 deg. F.

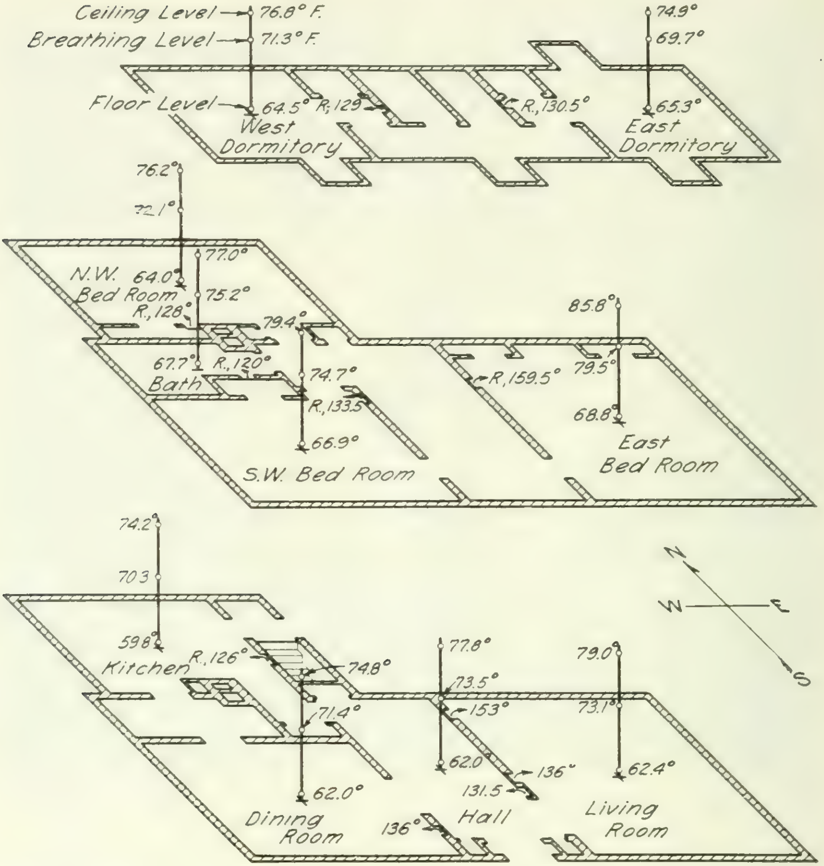

Fig. 10. Room Temperatures and Register Temperatures for All Rooms

During the hours when the outdoor temperature was at — 16 deg. F., and when the furnace fire had been without attention for several hours during the night, the average temperature at the breathing level in the rooms was 71.6 deg. F.

The temperatures given were obtained without dampering or adjusting any valves or registers, all were wide open. This demonstrates that a warm-air plant may be designed to give a good degree of uniformity in temperature in the different rooms heated.

In addition to the temperature at the breathing level, the temperatures 4 in. above the floor and 4 in. below the ceiling were determined by means of shielded thermometers supported on standards, shown in Fig. 9, which were located near the center of each room. The

TABLE 3

TEMPERATURES IN RESEARCH RESIDENCE DURING COLD WEATHER OF JANUARY 14-15, 1927

	First Floor				Second Floor				Third Floor		Average Inside Temperature	Outside Temperture
	Living Room	Dining Room	Kitchen	Hall	E. Bed. Room	S. W. Bed Room	N. W. Bed Room	Bath Room	E. Dormitory	W. Dormitory	deg. F	deg. F
Temperature taken at	Temperatures, deg. F.											
Ceiling	79.0	74.8	74.2	77.8	85.8	79.4	76.2	77.0	74.9	76.8	77.6	
Breathing level	73.1	71.4	70.3	73.5	79.5	74.7	72.1	75.2	69.7	71.3	73.1	
Floor	62.4	62.0	59.8	62.0	68.8	66.9	64.0	67.7	65.3	64.5	64.3	
Temperature difference noted between	Temperature Differences, deg. F.											—3.1
Ceiling and Floor	16.6	12.8	14.4	15.8	17.0	12.5	12.2	9.3	9.6	12.3	13.3	
Breathing level and Floor	10.7	9.4	10.5	11.5	10.7	7.8	8.1	7.5	4.4	6.8	8.8	
Ceiling Heights	8 ft. 11 in.				8 ft. 4 in.				7 ft. 0 in.			

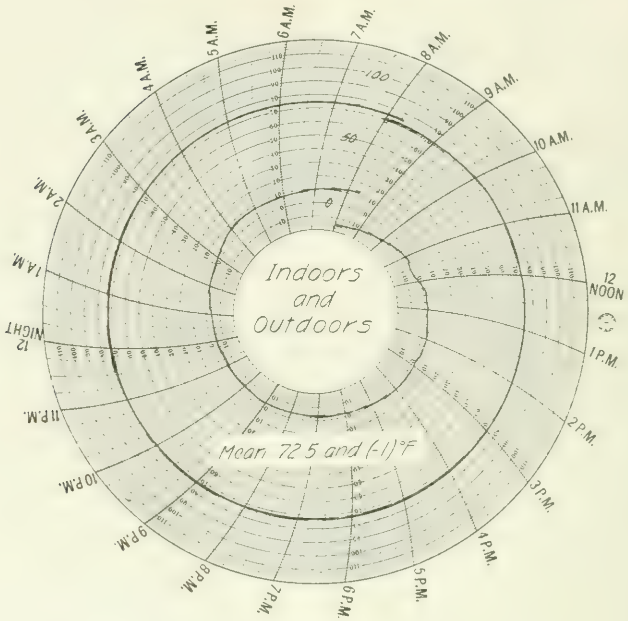

Fig. 11. Temperature Recorder Chart Showing Uniformity of Temperature in Residence

average readings of these thermometers are shown in Table 3, and also in the diagram, Fig. 10.

The difference in temperature between the breathing level and the floor is of much significance as a factor affecting human comfort. It is desirable that this difference be held to a minimum. For a given temperature at the breathing level, other factors being equal, the temperature at the floor depends on the outdoor temperature, and on the method of supplying heat and controlling the flow of heated air in the room. In a warm-air heating system the location of registers and return grilles has an important bearing on the temperature differential between head and feet. Hence the study of this temperature difference is stressed in the research residence work as the measure of the efficacy of various register and grille locations. The values given in Table 3 show that for the particular installation illustrated in Figs. 3, 4, 5, 6, and 7, in the most severe weather a difference of 10.5 deg. F. was experienced on the first floor, 8.5 deg. F. on the second floor, and 5.5 deg. F. on the third floor. Lesser differences have been obtained with other locations of grilles, but it is significant that observers re-

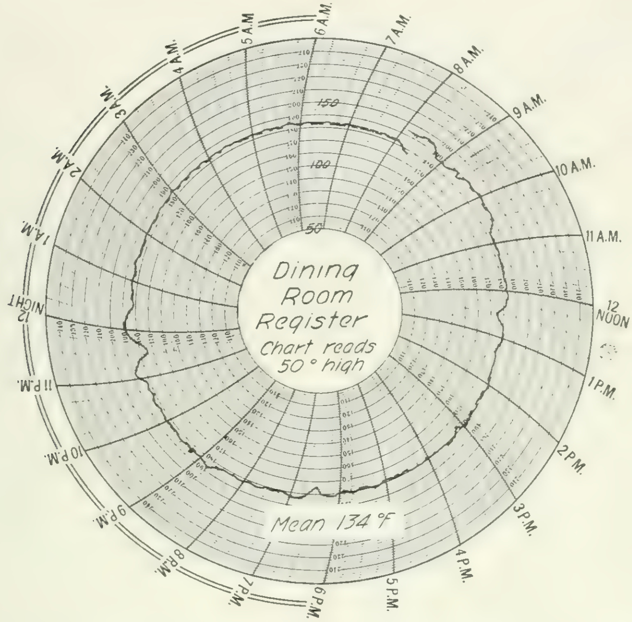

Fig. 12. Temperature Recorder Chart Showing Uniformity of Temperature of Delivery at Registers

ported themselves as being comfortable under these temperature conditions during this cold weather. Several of the rooms in which the data were obtained have three exposed walls with windows, a condition which makes the elevation of the floor temperature extremely difficult. In general, the results reported are considered as representing very satisfactory heating.

7. *Temperature Regulation.*—The supply of air to the fuel was under control of a dual, or balanced, system of two thermostats. One element in the dining room functioned as a simple thermostat, and another in the furnace operated to limit the furnace temperature. So responsive and positive was the action of this system that the dampers operated to open and close the draft door about once in fifteen minutes.

As a result the house temperatures fluctuated only 1 deg. F., and the air was discharged from the registers at the temperature required to make good the heat losses. The fluctuations in register temperature amounted to only 1 or 2 deg. F. Flue gas temperature fluctuations were confined to a range of 200 deg. F., a much narrower range than can be obtained with manual control. These conditions are shown in

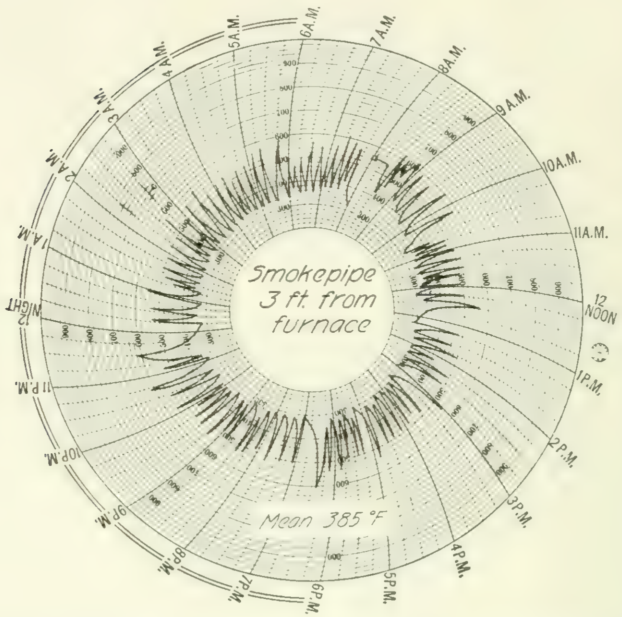

Fig. 13. Temperature Recorder Chart Showing Smokepipe Temperature and Frequency of Damper Operation

Figs. 11, 12, and 13, in which actual recorder charts are presented. The heavy waves in the lines of these charts mark the firing periods, the only times that regulation was disturbed.

8. *Register Discharge Temperatures.*—The average temperature of the air leaving the registers for the two day period was 135 deg. F. This moderate register temperature, obtaining during the most rigorous weather, is the distinguishing characteristic of a well designed warm-air heating system. The highest temperature observed at any time was 172 deg. F. at the register in the east bedroom. The average for this register was 160 deg. F. and reference to Table 3 will show that this room was heated to a higher temperature than any other room. The lowest temperature average was at the bathroom register, 120 deg. F., but this was enough to maintain the bathroom at 2 deg. F. above the average for the house.

These remarkably moderate register air temperatures exemplify the results which may be obtained with good installation practice. Any system in which friction and turbulence are minimized will operate at equally low temperatures.

9. *Velocity and Volume of Air Flow.*—The system tested was one of complete recirculation, and returned to the heater, through its three ducts, an average of 47 250 cu. ft. of air per hr. during the sub-zero weather. On the assumption that only the air in the open spaces of the house, 16 120 cu. ft., (about 45 per cent of the cubage of the house) would be recirculated, the equivalent recirculations were 2.93 per hr. Actually, each particle of air would not be passed 2.93 times per hour through the furnace, since a certain replacement and exchange due to inleakage at doors and windows is constantly in progress. Hence the term equivalent recirculations has been employed. It is this rapid turnover in the air contents of the house, combined with the admixture of fresh air,* which constitutes the ventilation feature of warm-air heating.

Through the three return ducts (Fig. 6) the average velocity of flow was 132 ft. per min. The east duct was slightly the most effective in proportion to size, a condition which might be ascribed to the influence of wind, since this duct was on the leeward side. The distribution of the air through the ducts was as follows:

	Percentage of Total Area	Percentage of Total Air Weight
West duct	36.8	36.7
South duct	36.8	35.6
East duct	26.4	27.7

On the hot side of the system the mean velocity of flow was greater than in the return ducts, by reason of the expansion of the air in its passage through the heater. This increase in volume, inversely proportional to the densities of the cold and the heated air (0.0753 and 0.0649 lb. per cu. ft., respectively), amounted to 16 per cent. At the registers, however, the mean velocities were greatly reduced by the larger area of the registers. The velocity, based on the nominal area of the registers, averaged 112 ft. per min. The velocity at the register of the most active pipe was 184 ft. per min. and the lowest velocity at any register was 65 ft. per min. It should be borne in mind that no pipe dampers or register valves were adjusted, and the velocities were not equalized by any device. The velocity in the upper-story pipes would be greater, by virtue of greater motive heads, than in the first-story pipes. Hence a wide range of register velocities should be expected, a factor of great importance in determining the relative size of pipes to the different floors.†

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*See Section 17. The terms "air change" and "recirculation" are not identical and should not be confused.

†See Fig. 71 p. 121, Univ. of Ill. Eng. Exp. Sta., Bul. 141. See also "Standard Code Regulating Installation of Warm-Air Heating Systems in Residence."

10. *Combustion Rate.*—The fuel used in the tests was anthracite coal,* stove size, of 12 996 B.t.u. per lb. heat value. Fuel was charged four times daily and the ashes removed once. To ascertain the actual consumption of fuel, rather than the coal fired, the fire was reduced to a fixed and marked level at the beginning and end of each 24-hour test, and correction made for the weight of carbon which fell with the ash as a result of this reduction in fire level. This process of determining fuel consumption has given very consistent results. The check draft was sealed. The fire depth ranged from 10 in. at starting to 18 in. at the end of each test. Under these conditions the combustion rate was found to be 3.3. lb. coal consumed per sq. ft. of grate per hour, and firing periods of 8 hours were easily possible.

11. *Draft.*—To produce this combustion an average head, or draft differential, of 0.04 in. of water was necessary to overcome the resistance of the grates, fuel bed, and furnace passes, and accelerate the flow of air and gases. With the particularly narrow setting of the draft door entailing considerable additional resistance the total draft required of the chimney was 0.14 in. of water.

The maximum differential draft observed at any time was 0.08 in. water and the maximum smoke pipe draft observed was 0.21 in. of water.

The chimney in the research residence is capable of producing greater drafts than are required, and to prevent too rapid acceleration of the gas flow a cross damper in the smoke pipe was set at about one-half closed. The draft values noted were taken with this damper set.

12. *Capacity and Efficiency.*—At the bonnet collars of the furnace a capacity of 72 600 B.t.u. per hr., of the total of 123 300 B.t.u per hr. of the fuel, was available, and the efficiency of the heater proper was therefore 59 per cent. Of the 72 600 B.t.u. per hr. capacity available at the furnace collars, 58 500 B.t.u. per hr., or 80.5 per cent, was available at the registers. Thus the loss of heat between heater and room amounted to only 19.5 per cent.

13. *Heater Losses.*—Since the furnace efficiency was 59 per cent it is evident that the balance of 41 per cent of the heat of the fuel was given up from the furnace through other channels than the circulating air. The possible sources of loss appear to be chimney losses and furnace casing losses. The chimney losses were studied carefully, and the results based on flue gas analysis and temperature, and coal analysis, were as follows:

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*Actual cost of anthracite in bin was $16.50 per ton.

Loss due to dry flue gas	12.6	per cent
Loss due to moisture and hydrogen in coal	2.5	per cent
Loss due to carbon monoxide in flue gas	4.1	per cent
Total at smoke pipe connection to furnace, per cent heat of fuel	19.2	

The remainder of the heat of the fuel consumed, or 21.8 per cent, was charged to radiation from the front, floor, bonnet, and casing of the heater, and to the evaporation of water. No exact accounting can be made of these losses. The average temperature of the casing proper, measured at ten places, was 116 deg. F., a relatively low temperature, and one which would permit of placing the bare hand on any part of the casing. However, the relatively large areas of casing, front, and bonnet are sufficient to bring about a considerable loss of heat, and estimates of this surface radiation, together with the heat energy required for the evaporation of water in the humidifier, account readily for 18 of the 22 per cent mentioned.

14. *Overall Efficiency of System.*—In the preceding section certain items were mentioned which, though not helpful to the efficiency of the furnace proper, were yet helpful in maintaining comfortable temperatures within the residence. In fact, only that heat which escaped from the top of the fully-housed chimney could be said to be not useful in heating.

Observation of the temperatures in the path of the flue gases showed the following results, the loss in temperature meaning that the heat was given up to the surrounding structure:

Temperature leaving furnace	498 deg. F.
Temperature at base of chimney	271 deg. F.
Temperature at top of chimney	152 deg. F.

The net loss in heat at the chimney top corresponding to this temperature of 152 deg. F., together with carbon monoxide and moisture losses, amounted to 11 per cent of the heating value of the coal. The overall efficiency of the heating system in the residence was therefore 89 per cent. As a check on this efficiency the calculated heat loss of the house for the particular weather condition, estimated by independent computers at 112 500 B.t.u. per hr., may be compared with the gross heat of the fuel consumed, 123 300 B.t.u. per hr., giving an efficiency of 91 per cent.

It appears, therefore, that 48 per cent of the heat of the fuel consumed was actually delivered at the registers, and another 41 per cent found its way into the building by radiation and convection from smoke pipe, chimney, casing, and piping. As further evidence of this indirect flow of heat it was observed that the temperature of the air between the joists over the furnace was 88 deg. F. This is more than 20 deg. F. warmer than the air above the first floor, hence a definite transmission of heat through the 2 inches of flooring was in progress. Simultaneously, the basement temperature at the breathing level did not rise above 62 deg. F. or 26 deg. F. less than that of the air above the furnace and between the joists.

15. *Effect of Snow on Roof.*—During the two-day period covered in this discussion the copper shingled roof of the residence was completely covered with snow to a depth of about 6 inches, and the effect on the temperature within the house was very marked. Thermocouples are attached to the shingles, and others are suspended in the rafter and attic spaces beneath. The temperatures observed at these points during the presence of snow, and at another time during the absence of snow, show the remarkably insulating effect of snow, and indicate the benefits to be derived from the use of commercial roof insulations.

EFFECT OF SNOW ON ROOF AND ATTIC TEMPERATURES

	With Snow Deg. F.	Without Snow Deg. F.
Outdoor temperature	—2	1
Shingles temperature	27	8
Rafter air spaces	54	42
Room below, near ceiling	74	66
Diff. between air space and outdoor	56	41
Diff. between room and air space	20	24
Diff. between room and outdoors	76	65

From the table it may be observed that beneath the snow the shingles were actually warmer than when there was no snow, a condition which shows the blanketing effect. This blanketing effect made the air beneath the roof 12 deg. F. warmer when the snow was on the roof, and reduced the temperature differential between air below the ceiling and air above the ceiling from 24 to 20 deg. F. This differential reflects the relative loss in heat through the ceiling and indicates a saving of the order of 17 per cent, which can be credited to the presence of snow. The last line of the table shows that the snow made possible much warmer conditions in the third floor rooms, as it was possible to maintain a much greater temperature differential between the room and outdoors when the snow covered the roof.

16. *Humidity and Evaporation.*—On these particular days the evaporator in use consisted of a concrete basin formed within the base ring of the heater. The water level, controlled by a float, stood at a depth of 1.5 in.; and approximately 6.5 sq. ft. of surface were exposed to air currents and to radiant energy from the hot furnace castings.

A thermometer suspended in the water in this evaporator showed a maximum temperature of 120 deg. F. The daily evaporation in the sub-zero weather was 61.6 lb. of water, or 7.4 gallons. Expressed on an hourly basis this evaporation was 2.56 lb., or 0.31 gallons. The ordinary domestic uses of water in cooking, laundry, scrubbing, and bathing did not exist in the research residence, hence humidification of the air was effected entirely by furnace evaporation, and by inleakage of air from outdoors.

The relative humidity actually obtained in the residence averaged 18 per cent. The humidity during the days preceding the cold wave had been much higher and the sudden drop in temperature had reduced the glass temperature below the dew point so that all window panes were more than half frosted on the first of the cold days. On the second day, however, the frosted area had diminished appreciably by evaporation.

A relative humidity of 18 per cent is scarcely ample for bodily comfort* at the house temperature of 73 deg. F. but with the additional evaporation from normal domestic processes there is no doubt that most satisfactory humidity, comfort, and health conditions would exist in the research residence. The evaporation of 1.5 gallons of water per day from an open pan in the kitchen of the residence, which is about equivalent to the normal domestic sources of water vapor in a house, had the effect of raising the relative humidity approximately 5 per cent.

It should be remembered that the windows and doors were not weather stripped nor was special care taken to seal the frames in place at the time of building. The walls were not insulated or filled, and the inner wall surfaces of rough sand plaster have never been painted.

17. *Estimate of Air Change.*—The outdoor relative humidity was 100 per cent and the indoor humidity 18 per cent. The water vapor supplied, 2.56 lb. per hr., is sufficient to humidify 14 500 cu. ft. of the

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*For comfort the required relative humidity for the dry bulb temperature 73 deg. F. of the research residence should be 20 per cent to give an "effective temperature" of 66 deg. F., a condition of comfort for most people, according to the researches of the American Society of Heating and Ventilating Engineers. See the Effective Temperature Chart in the Guide 1926-27 of the A. S. H. & V. E.

According to the findings of the Chicago Commission on Ventilation the relative humidity most desirable, at a dry bulb temperature of 73 deg. F., would be 24 per cent.

outdoor air to 18 per cent humidity at 73 deg. F. This quantity of air, 14 500 cu. ft., would appear to be the hourly inleakage and in terms of the circulating air of the house, 16 120 cu. ft., would amount to 0.90 air change per hour. This method of estimating air change is subject to uncertainties, such as unaccountable moisture given up from the building materials, and the result must be considered only as very approximate.

IV. Conclusion

18. *Conclusions.*—The results obtained were extremely satisfactory, both as regards effectiveness of heating and economy of operation, and warrant the following conclusions:

(a) A good degree of uniformity of temperature between the various rooms can be obtained with a well-designed warm-air heating system.

(b) Moderate temperatures at the registers, 135 deg. F. in this case in the coldest weather, are characteristic of a well-designed warm-air heating system.

(c) The rapid turnover of the air contents of the house, combined with the admixture of fresh air, constitutes a valuable ventilation feature of warm air heating.

(d) High over-all efficiencies can be obtained with a warm-air heating system; in this case the net loss of heat from the chimney was 11 per cent.

(e) Satisfactory relative humidity can be obtained with a warm-air heating system.

The results and data shown are for two days only, and when plotted with a mass of data for other weather conditions may not coincide with the graphical mean. However, representing as they do the extreme condition, they will have much to do with the determination of the graphical mean curves, and the variation from the curves should not, therefore, be appreciable.

For convenient reference the following tabular summary of data and results has been presented:

Summary of Observed Data and Calculated Results

1. Date	Jan. 14 & 15, 1927
2. Barometer	29.95 in. Hg.
3. Wind, direction and velocity	N. W., 7 mi. per hr.

4. Coal, kind	Anthracite, stove size
5. Coal, heat value	12 996 B.t.u. per lb.
6. Coal, carbon in	79.3 per cent
7. Coal, moisture in	2.3 per cent
8. Coal, ash in	12.1 per cent
9. Coal fired per day	232.5 lb.
10. Coal burned per hr	9.4 lb.
11. Combustion rate per sq. ft. grate per hr	3.3 lb.
12. Temperature outdoors, mean	−3.1 deg. F.
13. Temperature outdoors, range	−16 to + 10 deg. F.
14. Temperature, average of 10 rooms	73.1 deg. F.
15. Temperature, return grilles, mean	66.4 deg. F.
16. Temperature, bonnet, average	151.5 deg. F.
17. Temperature, boots, average	141.0 deg. F.
18. Temperature, registers, average	135.0 deg. F.
19. Temperature, flue gas, at furnace	498 deg. F.
20. Temperature, flue gas, base of chimney	271 deg. F.
21. Temperature, flue gas, top of chimney	152 deg. F.
22. Temperature, furnace casing	116 deg. F.
23. Temperature, basement	61 deg. F.
24. Air weight, return ducts	3558 lb. per hr.
25. Air weight, registers	3506 lb. per hr.
26. Air density, at return grilles	0.0753 lb. per cu. ft.
27. Air density, at registers	0.0649 lb. per cu. ft.
28. Air volume, return ducts	47 250 cu. ft. per hr.
29. Air velocity, return ducts	132 ft. per min.
30. Air velocity, registers	112 ft. per min.
31. Air recirculations	2.93 per hr.
32. Heat of coal burned	123 300 B.t.u. per hr.
33. Heat at bonnet collars (= Capacity)	72 600 B.t.u. per hr.
34. Heat at boots	63 800 B.t.u. per hr.
35. Heat at registers	58 500 B.t.u. per hr.
36. Heat loss of house	112 500 B.t.u. per hr.
37. Heat loss at chimney top	13 550 B.t.u. per hr.
38. Efficiency, as of furnace proper	59 per cent
39. Efficiency, as of registers	47.5 per cent
40. Efficiency, of pipes and stacks	80.5 per cent
41. Efficiency, overall of house	89 per cent
42. Efficiency, of grates	98 per cent
43. Draft, at smoke collar	0.14 in. water
44. Draft, differential, ashpit to collar	0.04 in. water
45. Carbon dioxide in flue gas	12.6 per cent
46. Carbon monoxide in flue gas	1 per cent
47. Evaporation of water	2.56 lb. per hr.
48. Relative humidity in house	18 per cent
49. Relative humidity, outdoors	100 per cent
50. Apparent air changes	0.90 per hr.

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